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Thin Film Studies of the Proximity Josephson Effects

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Final Technical Report, AFOSR Grant 91-0245

Title: " Thin Film Studies of the Proximity Josephson Effect", E. L. Wolf PI, Department of Physics, Polytechnic University, Six Metrotech Center, Brooklyn, NY 11201

Prepared September 13, 1993 by E. L. Wolf

I. Introduction

The topics of theoretical and experimental interest in this research have been:

The Proximity Induced Josephson Effect (PIJE), an effect occurring at a Normal Metal/Superconductor (N/S) interface which displays many of the features of the Josephson effect, the device potential of which has not been at all explored.

The design and construction of a cryogenic scanning tunneling microscope capable of operating in ultra high vacuum (see below).

The Proximity Induced Josephson Effect (PIJE) [1-4] has been observed at a Normal Metal/Superconductor (N/S) interfaces in point contact NS systems, and displays features resembling the Josephson effect. In experiments with Nb and Ta probes contacting Mo and UBe_{13} (normal state) surfaces [2,3], the I(V) exhibit a low resistance segment centered at zero bias current resembling a Josephson current with a small series resistance R^*, which has been interpreted as a spreading resistance in the normal state electrode. The basic interpretation is that the proximity effect induces pairs in the N electrode within a coherence length of its surface, and these pairs and those in the S electrode exhibit Josephson coupling. The effects were observed at temperatures up to an apparent junction critical temperature T^* which approached the T_c of the superconducting probe. It was observed that the apparent Josephson current split under microwave radiation [2] into steps with the conventional Shapiro step spacing. In some cases a Fraunhofer type magnetic field dependence of the critical current was observed.

In a second line of experimental work,"excess currents" seen near zero bias observed by Goldman and his colleagues [5,6] in thin film junctions of the form N-I-S. These effects were similar to but much weaker than those designated PIJE, and were accounted for by a second order Josephson effect model summarized by Kadin and Goldman [6]. A

theoretical model was advanced by Geshkenbein and Sokol [7] which seemed capable of describing both the PIJE effects including the RF steps, and the weaker "excess currents."

There remain questions, theoretical and experimental, concerning these very interesting effects. On the experimental side, use of point contacts made accurate determination of relevant parameters of the N/S or N/I/S system difficult. It was suggested by Kadin [8] that the effects in S upon N point contacts might arise by a phase slip center in the S tip, or even by the S tip fracturing into two parts which could form a conventional Josephson junction.

The present work was intended to find the same PIJE phenomena in evaporated thin film junctions, where one can make more reliable estimates of relevant parameter values. In a sense, this was an extension of the line of experimental work of the Goldman group to junctions of lower resistance and higher current density, corresponding to stronger coupling of the N and S electrodes.

However, an important advance in the work has been provided by changing to metal-degenerate semiconductor contacts, where even higher coupling of the N and S regions can be attained, by use of Schottky barriers and making use of the small effective masses m^* which have much higher tunneling probability. This will be described below.

The work was originally to have been carried out in collaboration with Dr. Laura Greene at Bellcore by Mr. George Keramidas, but he became unavailable after several months of preparation for the work by unfortunately being drafted into the Greek navy during a visit to his parents. Mr. Hang Zhang, an excellent Physics graduate student, then took over the research project. Mr. Zhang worked in the lab of Dr. Laura Greene at Bellcore, in Red Bank, NJ, from January 1992 through August, 1992. The results from that period of work were largely described in the first annual progress report on this grant. Unfortunately, Dr. Greene left Bellcore to accept an academic position at the University of Illinois, taking her laboratory equipment with her, in September 1992. Since Dr. Greene had to build a new lab at the new location, it was not feasible for Mr. Zhang to carry the project, depended on Dr. Greene's equipment, further.

Mr. Zhang had to return to our Polytechnic lab, being left with no sponsor at Bellcore. Since we have no facilities for the thin film project originally intended, Mr. Zhang decided to devote his time in the remainder of the present Grant to design of a cryogenic scanning tunneling microscope which will be used in developing nano-fabrication methods for high temperature superconductors under AFOSR Grant # F 49620-93-1124, entitled "Scanning Tunneling Microscope Methods for Fabrication of Mesoscale Cuprate Superconductor Electron Devices". It was decided that Mr. Zhang would be supported by this grant upon the termination of Grant 91-0245.

II. Results

A. Proximity Josephson Effects. The results in the area of the Proximity Josephson effect were described in the previous Technical Report for AFOSR Grant 91-0245, dated July 14, 1992. Due to the circumstances described above, this report represents the greater part of progress made on the Proximity Josephson effect in our laboratory under the present grant.

Experimental work on thin film N/I/S junctions was designed to make the tunnel barriers more transmissive and the possible PIJE regime more apparent, as predicted by the Geshkenbein-Sokol model which encompasses both the PIJE and "excess current" regimes. In consulting with Dr. Laura Greene and her collaborator, Dr. A. Kastalsky, the approach chosen was based on the planar junction technology. It had been earlier reported by Kastalsky, Greene, et al [9] that the degenerate semiconductor InGaAs could be induced superconducting by proximity to superconducting Nb. Excess currents and some aspects of the PIJE were present in the I(V) of such metal-degenerate semiconductor contacts, specifically Nb/InGaAs Schottky barrier contacts [10]. The motivation to try this system was that the Schottky barrier on heavily doped InGaAs has a low barrier height and high transparency. The former may be related to the small bandgap; this and the small effective mass of electrons in InGaAs both raise the tunneling rate through the Schottky barrier.

Mr. Zhang, working with Dr. Greene and Dr. Kastalsky at Bellcore initiated work to go one further step, replacing the InGaAs by n-InAs, still using Nb as the superconductor. This was expected to reduce the tunneling barrier between N and S, since it is believed that in an Nb/n-InAs contact a near flat band condition (no Schottky barrier) occurs in the n-InAs.

Mr. Zhang succeeded in fabricating and measuring several Nb/n-InAs planar junctions. The experimental system was Nb sputtered onto an n-InAs layer grown epitaxially on p-GaSb. The epitaxial layer of n-InAs, electron mass 0.02 and electron concentration 10^{17} to 10^{19} cm^{-3}, and 500 to 1000Å thick, was grown on the p-type GaSb. The extremely degenerate pn junction between the n-InAs and the GaSb has a negligible resistance. The Nb S electrode, patterned to 700Å on a side, and contacted with Au pads, was deposited on the epitaxial layer, after suitable surface cleaning of that layer. The semiconductor substrates were provided by Dr. Kastalsky; Mr. Zhang used a dc magnetron sputtering system in Dr. Greene's lab to clean the InAs surface and immediately to evaporate the Nb. The dynamic resistance dV/dI of the Nb/InAs structure was measured as a function of temperature and magnetic field by Mr. Zhang.

Several experimental problems were encountered in this barrier system which were not fully overcome before the departure of Dr. Greene from Bellcore. First, the n-InAs epitaxial layer was not made in situ but was imported into the vacuum system and then cleaned before the Nb is sputtered on. This cleaning is critical to getting a highly

transmissive barrier between the Nb and the InAs, which is central to the whole experiment. Several methods were tried, with results characterized by sputter-etching while observing the composition of the surface using Auger analysis. The Auger profiling was done after the Nb deposition and after a heating cycle was applied to put the Nb and InAs into even closer contact. The Auger spectra, after sputtering to remove most of the Nb film, still showed some oxygen and carbon contaminants in the barrier region, presumed to be carried in with the n-InAs epitaxial layer.

Electrical measurements on the tunnel junction devices showed some evidence of an excess current with a strong sensitivity to small magnetic fields at 1.2K. Unfortunately, only preliminary results were obtained before the laboratory was closed.

In the literature, several developments in this general area have occurred in the past year or two [11-15]. The first of these papers is an STM experiment which qualitatively reproduces the effects seen by Han et al [1,2] but with nanometer scale junctions formed by STM. These authors interpreted their work as a proximity induced Josephson effect, but one of the important tests, the Fraunhofer-like magnetic field dependence, was not looked for. In the work of Kastalsky et al [9,10], the Fraunhofer like magnetic field dependence was not present, but rather a non-oscillatory decay was observed. This makes it unlikely that the mechanism postulated in the work of Han et al was occurring in the junctions studied by Kastalsky et al.

Theoretical and experimental approaches to understand the strong magnetic field dependence without the true Josephson oscillatory behaviour have been described in the remaining papers [12-15] in an extension of the concept of Andreev scattering. This new theoretical approach is more economical in terms of assumptions and seems likely to explain most of the observations without as drastic assumptions as were made in the original and admittedly naive PIJE model of Han et al. The general impression at the moment seems to be that the work of Han et al [2,3] directed attention to an interesting and unexplored experimental regime in N/S contacts, the theoretical explanation of which has taken several successive turns. The phenomena are still being clarified experimentally and theoretically. The effect does involve transfer of pairs across an N/S barrier, does provide a nonlinear I(V) centered at V=0, and does exhibit sensitivity to magnetic field. However, it does not provide a supercurrent (strictly V=0, no dissipation) and does not exhibit an oscillatory dependence I(B). The strong nonlinearity in I(V) will make possible observations resembling Shapiro steps under microwave irradiation. It is still likely that device applications of the phenomenon will be found, e.g. in the "superconducting FET"; at the moment the understanding of the physics is still in a stage of rapid development.

B. Design of a Cryogenic Scanning Tunneling Microscope

The design of an STM which will allow clean surfaces and also achieve low temperatures brings challenges. Such an instrument is highly desirable to advance the understanding of cuprate superconductivity and to characterize the superconducting

behaviour of nanometer scale electron devices which may formed on surfaces of high T_c superconductors. For the former application, especially, atomic resolution at low temperature is needed, to measure variations over the surface unit cell. UHV preparation is needed in order to avoid disturbing the superconductivity by contamination; this is an especially important problem in high T_c because the superconducting coherence length in is so short, especially in the c direction.

The requirement of UHV means that a transfer gas is not allowed, so that conduction cooling of the STM must be arranged. Conduction cooling generally makes it harder to isolate the STM from the vibrations of the laboratory. This puts a premium on making the STM Head extremely rigid. It is also highly desirable to provide an electrical means of moving the tip and sample to within tunneling range, as direct mechanical connections are likely to bring in vibrations and to involve structures with low mechanical resonance frequencies.

The design of our STM head, which has been carried out by Mr. Hang Zhang under the present grant, is indicated in Figures 1-4. The unit as seen in Figure 1 consists of a frame being machined of Invar, with two 60 degree Vee grooves in the upper and lower portions. Springs, not shown, tension two triangular bars into these grooves, against piezo-electric shear plates, six on each triangular bar. The triangular bars can be walked along the axis of the device under the action of the shear plates; one triangular bar carries the tip and one carries the sample. The piezo electric shear plates are faced with polished sapphire plates which face the carefully polished faces of the triangular invar bars. In the walking action, a friction principle is used, following Dr. Shuheng Pan. The shear plates are individual slipped, and then returned in unison. The relatively heavy clamping of the whole system which can be maintained during the walking motion is an advantage in maintaining rigidity and insensitivity to common mode low frequency vibrations inevitably carried in from the outside. Work on other aspects of the cryogenic scanning tunneling microscope system is continuing.

Figure 1 The STM head configuration.

The tube scanner, spring and sapphire ball are not shown.

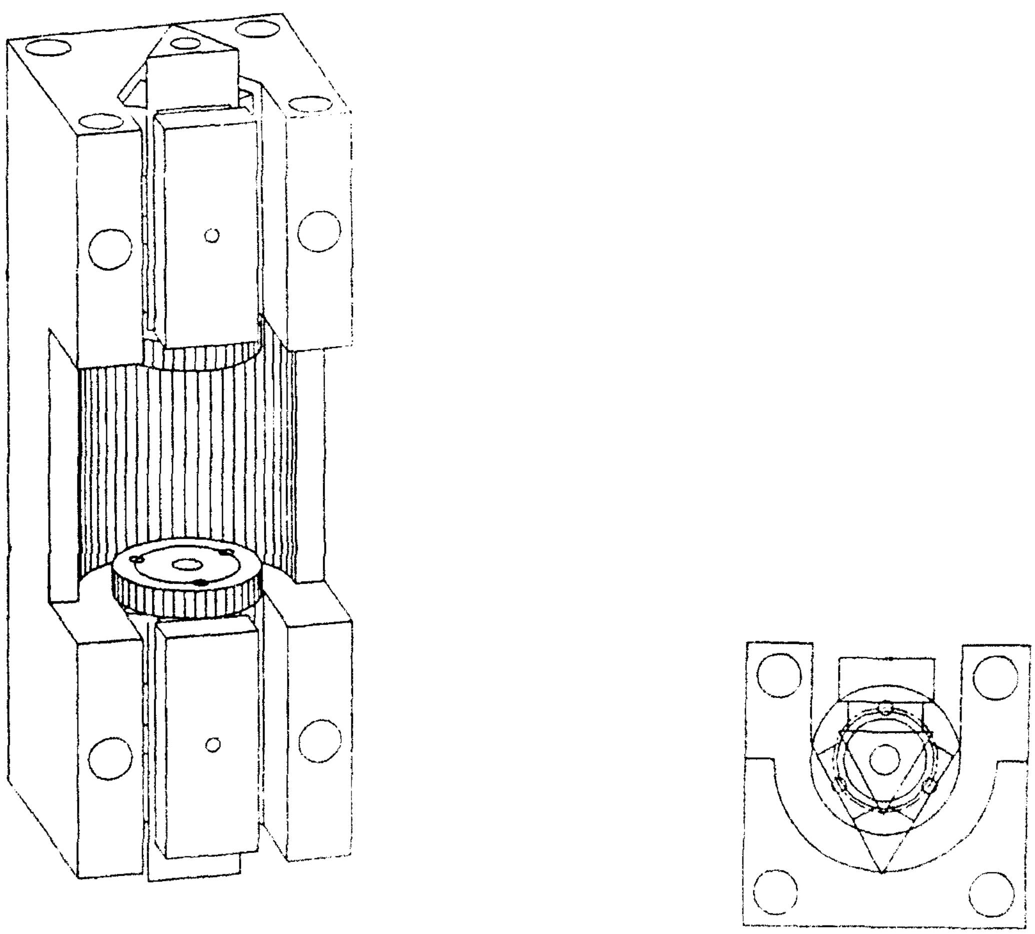


Figure 2 The 60 degree V-shape groove

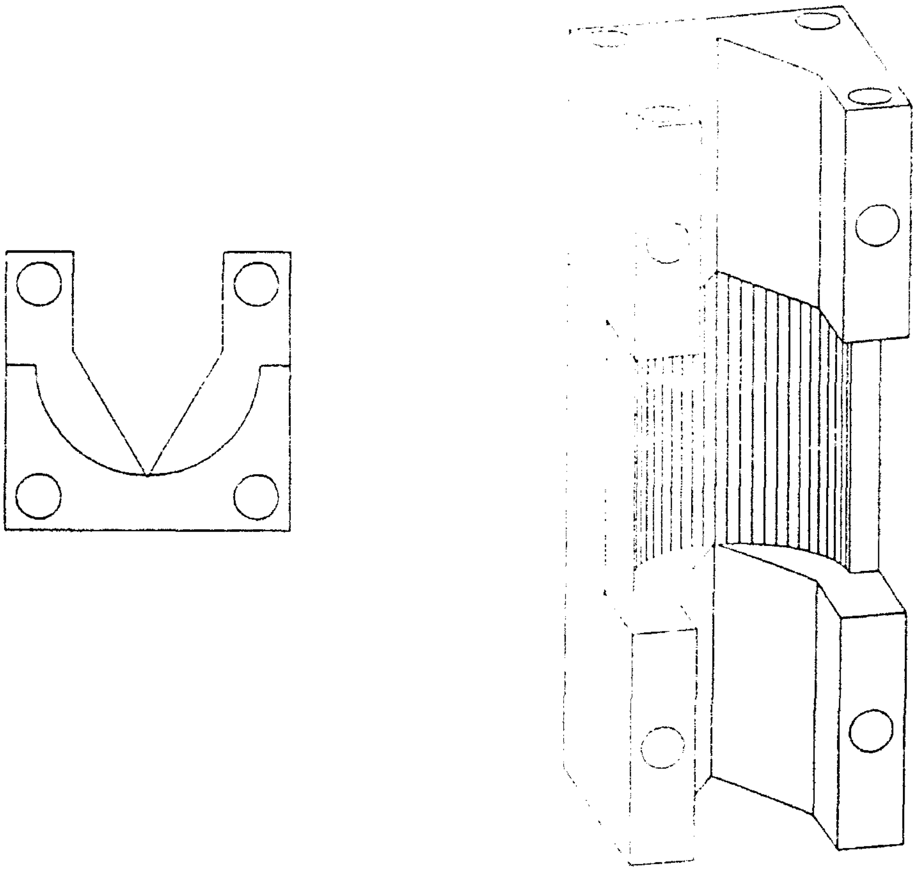
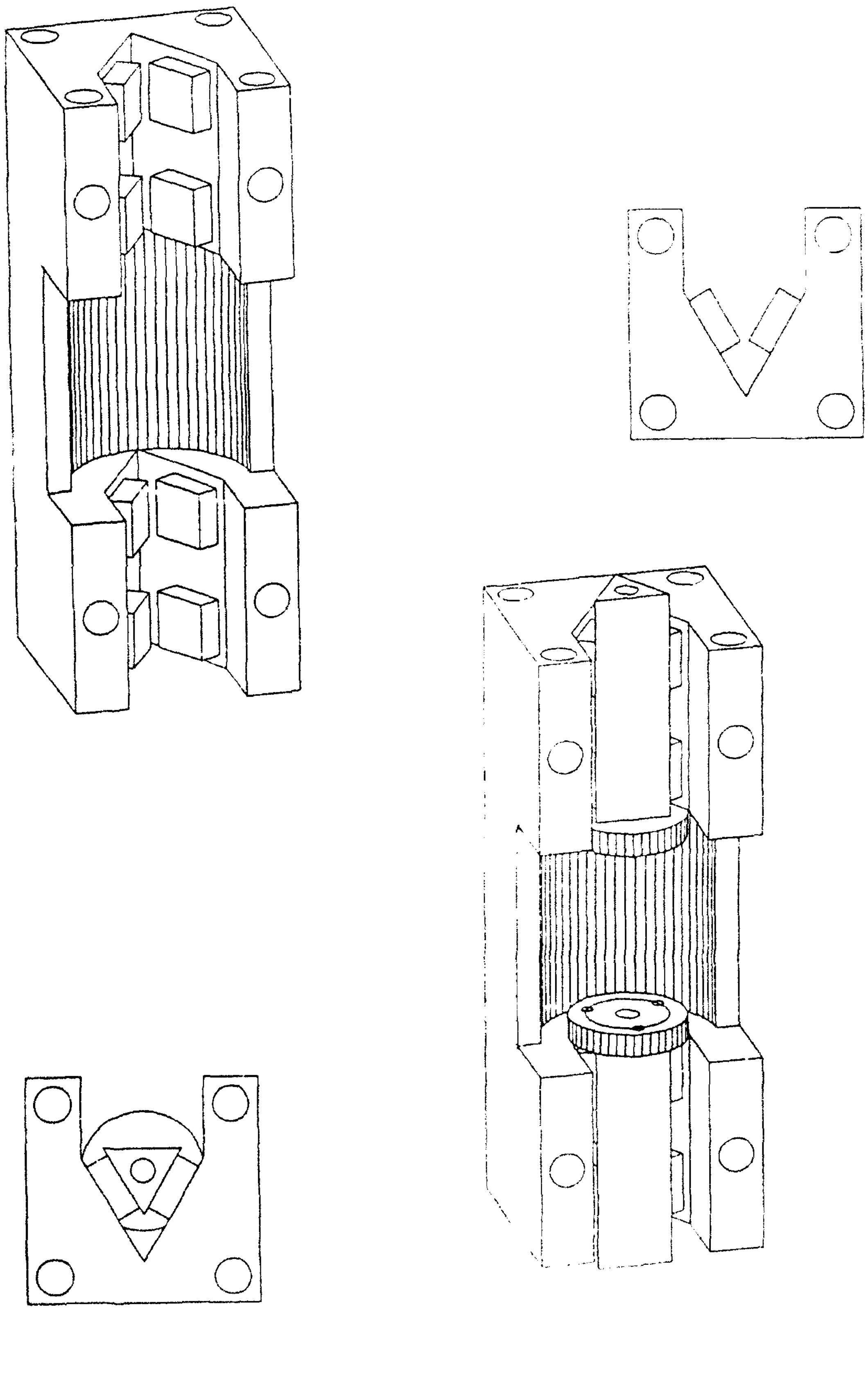


Figure 3 The walker

Figure 4 The piezo legs on the inner surface of the V-groove



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